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"Entropy-based Resource Management"; an organizing principle for the development of sustainability strategies.

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ABSTRACT:

This paper introduces how the "entropy-based resource management" organizing principle can be used to develop holistic, cost-effective resource management, land use planning and infrastructure development strategies to help communities achieve a more sustainable and resilient economy and environment.

Entropy-based resource management is founded on the recognition that natural systems always act to minimize energy loss and so leave each resource in its highest, most ordered thermodynamic state, i.e. in a state of minimum entropy, after each process has been completed. At heart, an entropy-based strategy is an attempt to create and maintain order in all aspects of resource management, taking aim at the second law of thermodynamics as the fundamental theorem describing how natural resources are utilized and impacted and so the key to developing effective sustainability strategies. In applying the organizing principle we are able to emulate how natural systems operate across physical boundaries for the efficient creation and storage, and frugal use of energy and natural resources, and to replicate their effectiveness in all our resource management activities.

The logical, physically based and comprehensive nature of the strategy gives it a wide range of applicability. From a physical standpoint, it is considered effective at both the micro (molecular) and macro (ecosystem) level and all levels in between. From a management standpoint, the organizing principle's logical approach and insistence on accounting for all resources at the same time helps reduce the number of discounted externalities in our management systems and minimize unintended consequences arising from implementation of those systems. Put simply, the organizing principle aims at ensuring that there are no logical inconsistencies or gaps between how physical processes actually function and how all our resources are managed and administered. As dwindling resources become ever more scarce, a management focus on achieving this basic goal becomes still more needed and urgent.

The paper first introduces the concept and describes some of the work products developed using this principle. Next, the paper suggests how use of the organizing principle can be effective in meeting newer challenges related to global warming and the introduction of smart technology and autonomous vehicles into our cities and infrastructure systems. Alternative formulations of the organizing principle that may help envision and develop new sustainability strategies are then briefly discussed. To assure effective implementation, the development of a sustainable land use plan, serviced by sustainable, resilient transportation and infrastructure systems that are further enhanced by Artificial Intelligence technology is envisioned.

KEYWORDS: sustainability, climate resilience, artificial intelligence.

1 Introduction

This paper introduces how the "entropy-based resource management" organizing principle can be used to develop holistic, cost-effective resource management, land use planning and infrastructure development strategies to help communities achieve a more sustainable and resilient economy and environment. The paper summarizes earlier work completed in a three-part series of technical papers for the Institute of Public Works Engineers Australasia [1] [2] [3] and two magazine articles for the American Public Works Association [4] [5].

Put simply, the objective of entropy-based resource management is to create and maintain order, both in the physical sense and administratively, in all our resource management activities. This focus on entropy offers us the full array of physical, chemical and biological ways to achieve that one fundamental objective.

The organizing principle, in its most basic form, requires that due consideration be given to energy, air and water at all times, the building blocks for maintaining life in the city. This is achieved, as much as possible, using simple but comprehensive and all-inclusive sustainability strategies. We're seeking to find what we may have missed by not applying holistic management practices up until now, and we also want to know how using an applied physics approach might improve the effectiveness of strategies and practices that we are already doing.

The organizational principle was first applied in the field of water resources and watershed management. A subsequent literature review found many instances where entropy-based analyses had been used in transportation planning, and by extension in the development of land use plans. Further work also suggested that the organizing principle could be used to help meet other current challenges related to global warming and the introduction of driverless cars, smart technology and Artificial Intelligence software into our lives, cities and infrastructure.

This paper introduces and summarizes some of the key elements of this body of work. The reader is referred to the original material for additional information and more detail.

2 Entropy-based resource management

"Instead of engineered stormwater facilities, why don't you use holistic, watershed-based methods that mimic natural processes?" This criticism was levelled at Clark County during the development of their mid-90s watershed plans. When trying to achieve basic engineering objectives, attempting to mimic natural processes does appear to make sense:

- Natural processes are highly efficient; mimicking them could be very cost-effective;
- Natural processes seamlessly interact and work across physical, chemical and biological boundaries; they are truly holistic; and,
- All natural processes are very efficient, not just the one your program is focused on at the moment but all downstream processes that follow.

So a strategy that mimics natural processes shows promise as effective resource management. But what does "mimicking a natural process" mean, in physical terms? The premise behind this strategy is that natural systems always act to minimize energy loss and so leave each resource in its highest, most ordered thermodynamic state, i.e. in a state of minimum entropy, after each process has been completed.

Continuing with that hypothesis, an entropy-based management system for any particular resource would attempt, after every internal process has taken place, to leave that resource:

- In its highest state of matter, i.e. solid phase;
- In the highest energy state, i.e. potential energy; and,
- At the highest level of potential energy possible.

In doing so, entropy-based management is able to emulate how natural systems operate across physical boundaries for the efficient creation and storage and the frugal use of energy and natural resources. It is considered to be applicable from the molecular level up to and including large-scale ecosystems.

2.1 Natural examples

As indicated earlier, any system that manages a resource efficiently would favour conserving that resource in its most ordered state, that is in solid phase with high potential energy. That system and similar systems would also be expected to be ubiquitous in nature. Are there any such examples in the natural world?

If we take as our resource the annual rainfall falling on a watershed, then snowpack appears to fit the bill. Snowpack along watershed ridgelines is water in solid phase with the highest possible potential energy. The "knock-on" benefits of having a good snowpack need no further explanation to watershed managers and biologists; maintaining snowpack constitutes good, holistic management of the water resource and everything else in the watershed.

Although the snowpack example appears to support our hypothesis, that example may be of limited value to a watershed manager. Physically creating snowpack, by cloud seeding or other methods, is beyond the means of most communities. So what might the next best thing be?

High groundwater is water in liquid phase with high potential energy. From our knowledge of how watersheds, wetlands and streams work, we know that maintaining high groundwater elevations can be expected to conserve water effectively as well as generate multiple downstream environmental benefits.

We now have something that a watershed manager can use. A simple entropy-based strategy for effective watershed management might be to promote the establishment and maintenance of high groundwater elevations in all the regulatory, planning and capital construction activities that the watershed manager can influence.

2.2 Use as an "organizing principle"

We noted earlier that natural systems will always act to minimize energy loss. Recall also that an entropy-based resource management strategy mimics natural systems to create and maintain order in all our natural resources.

Proceeding from these two observations, it seems logical for us to also attempt to mimic natural systems to try to reduce *organizational* energy losses (organizational inefficiencies) by establishing and maintaining order in all our management systems.

For example, from a capital program perspective, we can achieve this by moving as quickly as we can, expending the least effort possible, from a well-considered watershed improvement concept into on-the-ground construction of a needed project.

To be able to achieve this, our analysis and decision-making methods should be:

- *As simple as possible…*
  (i.e. accomplished using the least effort needed to assure a successful outcome)

- *…. but no simpler*
  (i.e. our thought processes, analysis and decision-making must be holistic and address all natural resources).

To best meet those needs the entropy-based resource management strategy is used here in the form of a simple "organizing principle" for developing sustainability strategies.

The overall strategy can be thought of as a "back-to-basics" approach to sustainability, favoring good judgment and holistic, well-reasoned decision-making over the use of complex methods based on elaborate research and the collection of large amounts of data.

2.3 Application

The first, most basic application of entropy-based resource management is the "do-nothing alternative", that is to allow natural processes to continue doing as they have always done. To simply trust that natural systems will perform better and more sustainably than a system that you as an engineer could devise, even with all the planning, data-collection, analyses and computer modeling that you may have at your disposal.

This initial step not only covers preservation activities but also requires you to first *use* natural processes as much as possible, then to always work in a top-down sequence when developing sustainability initiatives. Mimicking natural processes with your own engineering designs would also be a sound choice from that point forward.

In following these steps, we are acknowledging that the fundamental physics of how natural systems operate is efficient and will always produce beneficial outcomes. This recognition frees us to be able to make simple, well-informed judgments on whatever issue is in front of us at the time. We can then move forward expeditiously on sustainability initiatives, having used only limited quantification but still being confident that we will achieve good outcomes.

Because we have that confidence in good outcomes, the detail and accuracy in our *quantification* need only be sufficient for us to be able to make reasonable policy decisions. For example, in many situations we need use only “apples to apples” comparisons rather than highly detailed computer modeling. Those simple procedures, logical, orderly and achieved with minimal effort, are perfectly adequate to allow us to go quickly to a reasonable solution to a known problem.

3 Water resources and watershed management

The organizing principle was developed and first applied to watershed management. Brief descriptions of some early applications are provided below.

3.1 Hydrologic and hydraulic accounting

Hydrologic and hydraulic accounting are two simple techniques that use powerful and sophisticated hydrologic and hydraulic software in very simple ways to quickly identify needed and cost-effective watershed rehabilitation projects.

Hydrologic accounting uses a continuous-simulation hydrology model (WWHM) to compare two or more stormwater project alternatives based on the computed size of the hypothetical upstream watershed that they can “fully mitigate” (from a water quality or flow control standpoint).

Hydraulic accounting uses a sediment transport module within hydraulic river analysis software (HECRAS) to compare the annual sediment load generated by two alternative watershed rehabilitation plans, both acting upon a single, idealized stream reach. The mitigation plan with the least annual export of sediment from the basin is selected.

The 2008-2011 Stormwater Capital improvement Program (SCIP) made extensive use of hydrologic and hydraulic accounting procedures to identify, compare and prioritize stormwater mitigation and watershed improvement projects. Those simple analyses were completed without extensive study, data collection and analysis, so that the county was able to move projects forward quickly into construction.

3.2 Clark County Amphitheatre sub-basin retrofit plan

Here the organizing principle was used to develop a simple *game plan* to “pump up the groundwater as high as possible then plant everything”. In other words, store as much as possible of the annual precipitation and maximize photosynthesis throughout the watershed.

The Amphitheatre plan accomplished this in a series of simple steps:

Step 1: Develop Infiltration Zone Mapping and Matrix

Infiltration Zone maps and an associated Infiltration BMP Matrix were developed to identify the most cost effective stormwater infiltration BMP that could be used under any of the soil and groundwater combinations found in county watersheds.

Step 2: Develop “Maximum Improvement” plan alternative

Starting at the top of the sub-basin and working downstream, the Infiltration Zone maps and matrix were used to site the most cost-effective infiltration/retention BMP at every feasible stormwater retrofit location. The aggregated projects form the “Maximum Improvement” plan alternative.

Step 3: Alternative Analysis; Phase 1

In Step 3, additional plan alternatives were developed simply by reviewing the hydrologic accounting summations and deleting the least cost-effective individual BMPs. This quickly identifies two or three more affordable plan alternatives for more detailed analysis.

Step 4: Alternative Analysis; Phase 2

In this final step, hydraulic accounting computations were used to model the remaining plan alternatives in more detail, and as systems rather than as a collection of individual BMPs.

As indicated earlier, the selected sub-basin retrofit plan was the plan alternative that resulted in the least export of sediment from the sub-basin that could be achieved within the available budget.

3.3 Sustainable land use plan (water resources)

Cougar Creek, an urbanizing basin tributary to Salmon Creek, was used as an example to try to develop a sustainable land use plan. The annual rainfall supply was selected as the resource of concern.

The plan was developed in a four-step procedure that used available GIS information to develop a series of maps:

Step 1. Current Comprehensive Plan

The first map used was the current adopted land use plan, mostly econometric and transportation-based.

The goal was to develop a new plan with the same mix of land uses but distributed throughout the watershed in a way that would produce less impacts, cost less and be more sustainable.

Step 2: Use a groundwater flow model to determine the best arrangement of land uses

The assumption here was that the most sustainable land use arrangement would be the one that produced the highest groundwater elevations throughout the watershed.

The method used was to:

- Assign groundwater recharge and discharge values to Industrial/ Commercial, Residential and Parks/Open Space land uses;
- Place each of those three generalized land uses in the upper, middle or lower regions of the watershed;
- Analyze alternative land use placements using a groundwater flow model (Modflow) to compute the resulting groundwater elevations; and,
- Determine the optimal arrangement of land uses i.e. the one that produced the highest groundwater elevations.

Step 3: "Envirometric Overlay"

The Envirometric Overlay map was developed based on the outcomes from the groundwater model, and sited land uses where they would maintain the highest groundwater elevations throughout the watershed.

The solution worked out to be Residential at the highest elevations, Parks/Open Space in the headwaters and valleys, and Industrial/ Commercial in the lower watershed.

Basically, place the land uses with the most *net recharge* in the highest locations in the watershed and avoid adding new groundwater drains.

Step 4. Sustainable Land Use Plan

The last map was a simple compromise between the original Comprehensive Plan and the Envirometric Overlay. It showed the final revised zoning plus some associated new infrastructure.

3.4 Other Clark County initiatives

Other county work products developed using this strategy include:

- A watershed water balance approach was used to re-establish the natural drainage patterns, recharge functions and groundwater elevations in a degraded headwater wetland;
- Increased use of trench dams in drainage and utility pipe trenches; and,
- The successful defense of a county road-widening project against a legal challenge that the increase in impervious area would reduce groundwater recharge and so impact adjacent wetlands.

4 Energy, transportation and land use planning

Applications of the entropy based resource management organizing principle in the energy, transportation and land use planning fields are discussed in this section.

4.1 Sustainable roadway grid

At a roundabout, a car moves through the intersection without stopping. At a traffic intersection stop light, the car engine is running and using fuel but the car is not going anywhere. This is an unnecessary and unproductive increase in entropy (an entropy change from a liquid with high potential energy to a gas with high kinetic energy).

Recognizing this, we can see that we may be able to develop a lower entropy, more energy-efficient roadway grid by replacing a series of traffic signals with a roundabout corridor that allows continuous traffic flow without forced stoppages.

We can extend the entropy-based resource management strategy one crucial step further, by incorporating "green street" features such as roadside rain gardens within the roadway cross section. The roadway grid now combines the most sustainable energy use design (and lowest emissions) with the most sustainable water resources design.

The hypothesis was checked by comparing the two competing roadway designs for a hypothetical one-mile roadway corridor. The results showed a reduction in energy use, confirming the roundabout corridor alternative as the more energy-efficient. The roundabout corridor alternative also out-performed the signalized intersection corridor for all other air quality, water resources, environmental and cost metrics.

With its frugal use of energy and water and lower greenhouse gas emissions this entropy-based roadway design gives us truly holistic and sustainable roadway grid system.

4.2 Entropy-based analyses in transportation and land use planning

To advance the theory from its original water resources foundation, and to identify possible link-ups and cost-sharing opportunities between water and energy management, a literature review of available entropy-based transportation analysis methods was completed. It became evident from even a brief literature search that entropy-based analyses play a key role in the optimization of transportation systems. Through that function, entropy-based transportation planning techniques can then ensure that effective energy use is embodied within good land use plans.

The ubiquity of entropy-based methods used in traffic analysis also points to the likelihood of using those methods, along with their supporting mathematical techniques, to develop algorithms needed for the introduction of autonomous vehicles and driverless cars into the transportation infrastructure.

5 Meeting other current challenges

Although sustainability remains the primary objective of this line of research, other important areas are of urgent interest and may also benefit from the use of entropy-based management techniques. This section briefly reviews some of those areas to see if using an entropy-based resource management approach can be useful.

5.1 Climate resilience

While it is important that work on sustainability continues apace, attention more recently has shifted to the pressing need for resiliency measures to cope with climate changes brought on by global warming. In reality, sustainability and resiliency may be two sides of the same coin, and entropy-based resource management can help develop solutions that will work for both:

- Entropy-based transportation policies and planning can develop road networks that lower the work requirements for home-workplace travel, while new hybrid and electric vehicles can travel those networks more efficiently. Both energy-focused sustainability strategies also help reduce greenhouse gases, satisfying a key resiliency need.
- Maintaining high groundwater elevations by capturing and infiltrating stormwater runoff can help reduce the severity of droughts. That same water supply strategy will also help lower increases in flooding brought on by climate change.

As problems of various kinds develop from climate change, the need for a sound physics approach coupled with the use of powerful mathematical techniques to find optimized solutions will grow. The entropy-based resource management organizing principle can provide a useful and effective framework for developing those solutions, and entropy-based mathematical analysis can then help refine and optimize the resulting resource management strategies.

5.2 Driverless cars and autonomous vehicles

The introduction of driverless cars will create a still greater need for optimized traffic management systems. With human-made travel choices being supplanted by computer software, the need for sound, physically based algorithms that can fully optimize "electronic choice-making" will increase.

We've seen previously that entropy-based strategies are good at minimizing energy use and so can be valuable in designing efficient roadway networks for all vehicle types. We've also seen that entropy-based mathematical analyses can help optimize choice in making travel decisions, and so can also help with in-vehicle decision-making. This can be either by human drivers or by computer software incorporated into autonomous vehicles and driverless cars.

Based on the information found in the literature review, it appears likely that entropy-based traffic management strategies and their associated mathematical analysis techniques will play an important role in developing both the transportation systems and software that will be needed to successfully bring autonomous vehicles and driverless cars into the transportation system.

5.3 Smart Infrastructure and Artificial Intelligence

After effective transportation systems are established, AI-enhanced "smart infrastructure" can then help operate and maintain transportation and other public infrastructure systems effectively.

Of course, a rigorous, comprehensive application of the organizing principle would then require that all roadways use green street elements in-between intersections, to give us a truly sustainable roadway network. Entropy-based strategies covering energy, air and water, the building blocks for life in the city, will now have been integrated and will work together to produce an outcome that is truly "more than the sum of its parts". We now will have a truly holistic and sustainable infrastructure system, cost-effectively serving a thriving city population.

6 Alternative frameworks for strategy development

The series of technical papers has put forward entropy-based resource management as the outcome of a search to find a physical expression for the holistic management of our natural resources. Without detracting from that fundamental expression, this section discusses how the organizing principle might be viewed in different ways, i.e. alternative "formulations" or "frameworks", to help visualize and develop sustainability strategies.

6.1 Identify and eliminate "disorderly processes"

This is probably the most straightforward interpretation of the entropy based resource management concept, to attempt to minimize "disorder" wherever it is found.

In the physical sense, snowpack, as water in solid phase with high potential energy, can be considered as water in its most "ordered" form. Any process that accelerated the melting of snowpack, then, could be considered to be "disorderly" and so would be a process that we would work to improve. Viewed from that perspective, global warming and associated climate change are disorderly physical processes that we would like to find ways to minimize.

This *disorder* framework can also be usefully applied in an analogical way to help identify inefficient and wasteful systems, policies and practices wherever they exist. This can be done by asking simple questions aimed at determining whether current management practices are entirely logical (an orderly, efficient process) or are to some extent illogical (a disorderly or wasteful process).

For example, when tasked with comparing the different energy options you have available for commuting to work, you might ask the logical question "Why commute at all?" With the advent of powerful computers, telecommuting, essentially commuting at the speed of light with near-zero energy use, has been possible for some time. However it has so far been only sparsely used and can be viewed with suspicion by employers. We now see that is not a sound telecommuting viewpoint, which in many workplaces may have led to illogical, *disorderly* telecommuting policies.

Let's now consider water resources. There, asking the logical question "What good is all that groundwater recharge if you just drain it all away again?" led to Clark County's increased use of trench dams to counteract the french drain effect of porous backfill in pipe trenches.

Asking these types of simple, logical questions as to whether a particular management process is "orderly" or "disorderly" can help us develop more efficient practices, processes and systems. Order in the physical sense and its analogues (when applied to management processes) are entirely compatible, so opening up another rich vein of potentially effective resource management possibilities.

Note that with Covid-enforced telecommuting we are essentially operating a pilot entropy-based energy policy right now; one that eliminates some forms and quantities of work before considering the relative efficiency, negative impacts, etc. associated with using other competing forms of energy to complete the remaining essential work tasks.

Telecommuting is not viewed as an entropy-based sustainability strategy. However, since it reduces the total aggregate amount of work needed to complete any task or series of tasks, it is in effect one of the most essential, and one of the first that should be considered in any energy policy. Note too that its holistic nature as an energy saving and climate change response strategy comes with a very important side-benefit at this time i.e. protection against a spreading pandemic. In that sense, a hybrid part home-part office work policy may be viewed as resilient, whereas a solely office-based work policy would not. If you think and act holistically, using an entropy-based approach, you will get good system efficiency improvements along with valuable additional benefits, system resiliency being a particularly important one.

6.2 The efficient storage and frugal use of resources

Entropy-based resource management may also be formulated as "the efficient storage and frugal use of all the resources we need to sustain ourselves".

Efficient storage

"Storage" here, in entropy terms, is a desired product of the "create negative entropy" action outlined in earlier technical papers. One example might be the conversion of untapped natural wave energy into useful electrical energy, either distributed immediately or stored in some form for later use. Efficient storage might also simply apply to practices that facilitate the effective, non-wasteful storage of needed resources, one simple example being the use of refrigeration to make food resources last longer.

It is within this storage framework that the true value of the organizing principle's fundamental water resources strategy, the establishment and maintenance of high groundwater elevations, becomes clear. When we find ways to maintain high groundwater elevations throughout our watersheds (water in liquid phase at high energy levels) we are also storing as much as possible of the annual rainfall supply within the watershed, so maximizing its availability to ourselves and everything else in the watershed.

Frugal use

"Frugal use", in entropy terms, may perhaps be thought of as slowing down the rate that disorder is taking place.

The sustainable roadway grid suggestion noted earlier is one example of the frugal use of resources. That strategy minimized the travel time through a roadway corridor by using roundabouts rather than signalized intersections. By doing so, the amount of energy needed to travel that corridor, for any and all vehicles, was reduced.

Reviewing the strategy in physical terms, this frugal use of energy was accomplished by lowering the transportation system entropy by promoting smoother, more efficient traffic flow, so reducing the conversion of liquid petrol into gas.

Note that consistency with the earlier *disorder* framework can also be demonstrated with this same example. The logical question to ask might be "If I can travel from A to B in a shorter time using a roundabout corridor design, why would I care what maximum speed I was allowed to reach?" Why indeed. And the added safety advantage of traveling through a busy corridor at lower speeds would also be an important side-benefit of using this holistic, entropy-based energy strategy.

The frugal use of resources is perhaps where public works engineers and public planning agencies can have the most influence on and perhaps the most opportunities to contribute to sustainability. We don't often create new forms of useful energy, but we can certainly design transportation systems and road networks that allow all users, regardless of their preferred mode of transport, to use energy resources frugally. The following sequence of planning actions can help illustrate:

- Minimize ancillary work, i.e. the effort needed and resources expended before you even get to do your job. *Develop policies that maximize telecommuting.*
- Encourage human-powered work, walking, cycling, etc. *Promote multi-modal transport systems.*
- Reduce distance, travel time and energy expended between home and the workplace. *20-minute neighbourhoods, roundabout corridors.*
- Promote and facilitate efficient forms of travel. *Establish mass transit networks.*

As noted earlier, good land use planning can shorten the distance from home to your place of work, while multi-modal transportation systems and networks can then facilitate use of the most efficient energy types possible, so minimizing the total energy needed once some level of travel becomes unavoidable.

6.3 Use holistic methods that mimic natural processes

This is the original framework from which the organizing principle was developed. It can still be a very powerful formulation in helping to develop solutions to some of the more complex, seemingly intractable problems we face. We watch what natural systems do (always successfully) then model our own management systems on them.

Noting simply that water flows downhill, we:

- Make our roads slope towards a grated inlet to shed water from the driving surface and capture that runoff.
- Add a downhill slope on the outlet pipe to lead that water to where we want it to go (without the need for expending additional energy).

Those two engineering designs are made possible by observing and identifying the fundamental driving factors in what we know can be a fairly complex hydraulic process, and simply mimicking them. They are sufficient in many instances to accomplish the task of removing water from the roadway to give us a safe driving surface, and in most cases we can leave studying and developing more detailed hydraulic design criteria, such as flow spread and inlet interception calculations, to some later time.

That same simple design approach can be followed in many other complex situations, allowing us to favor action over inertia in important areas where complete understanding is for the time being unattainable but where action may nonetheless be urgently needed.

This series of papers has put forward entropy-based resource management as a useful organizing principle for developing holistic strategies, that is strategies having outcomes where "the whole is more than the sum of its parts". A literature search for *holistic strategies* could be very productive in your own field of interest when you are trying to find an effective resource management strategy.

Similarly, some closely related modern strategies that use *symbiotic* or *synergistic design* and *biomimicry* are also very consistent with the organizing principle.

All the above strategies might be considered as coming under the umbrella of entropy-based resource management, and can also be expected to bear fruit in the search for new sustainability initiatives.

7 Implementation

This section describes recent Clark County progress on implementing elements of entropy-based resource management. Following that are brief notes on other national and international initiatives considered to be good examples of the type of strategy that might emerge from using an entropy-based resource management approach.

7.1 Sustainable roadway grid: NE 10th Avenue; NE 149th Street to NE 164th Street

This 1-mile road project was Clark County's first attempt at constructing a "sustainable roadway grid" project.

The conceptual design included a multi modal roadway cross section, including sidewalk, bicycle lane and vehicle lane, within a 3-roundabout roadway corridor. Roadside bioretention cells (rain gardens) were used for stormwater runoff disposal and groundwater recharge.

Late in the design process, the roundabouts were eliminated due to county citizens' unfamiliarity with their operation (roundabouts are relatively new in the Clark County area). Also, poorly infiltrating soils and the presence of steep slopes precluded using roadside bioretention cells along much of this 1-mile corridor.

The 10th Avenue experience served to improve the county's design capabilities and also to gain knowledge of the issues and difficulties that can arise from implementing the strategy. Although having only limited success at the time, roundabout corridors and roadside bioretention cells are now becoming more acceptable to our citizens and policy makers.

The example of roundabout corridors is particularly instructive in the following way. Although initially presented to decision-makers as an energy-saving/pollution-reduction measure, their growing acceptance now is based on improved mobility and safety performance. Because of the multiple benefits they achieve, holistic designs may be accepted more readily due to what you may initially have thought of as their secondary benefits, rather than the primary purpose they were originally developed for. This aspect of entropy-based design can have great utility in describing strategies to different audiences, and in securing grants and other funding to complete infrastructure improvements.

7.2 Other Clark County initiatives

Following is an update on other Clark County initiatives. Some were direct outcomes of using an entropy-based approach while others were developed independently of that approach but exemplify the types of strategies that might emerge from its use.

Sustainable Land Use Plan

An introduction to the concept has been made to the Clark County Community Development Department. However, with such a new and expansive strategy, further investigation by a research institution is recommended before any further action.

20-minute neighbourhoods

The City of Vancouver recently adopted the Heights District Plan, Clark County's first 20-minute neighbourhood, where residents will have easy walking and cycling access to many of the places and services they use daily. These neighbourhoods minimize the use of cars and fossil fuels while maximizing the use of human power, at the same time providing health benefits for citizens. People also simply enjoy living there.

The 20-minute neighbourhood is an example of an energy policy with multiple positive benefits and no negative impacts. This type of work-minimization and energy-optimization measure lies front and centre of achieving an orderly energy strategy, which is itself a key component of any effective land use plan.

Infrastructure Coordination Group

This suggestion to manage the county's separate capital programs more holistically is aimed at providing cost sharing, scale economies and other opportunities to help meet the county's diverse infrastructure needs and Comprehensive Plan goals. Although some improved coordination has occurred between capital programs, the formation of a steering group has not yet been completed.

Sub-basin Retrofit Plans

The development of sub-basin retrofit plans as previously described is now established practice in the county's Stormwater Capital Improvement Program.

Hydrologic and Hydraulic Accounting

These are simplified analyses used to quickly identify effective stormwater capital projects. Hydrologic Accounting procedures are regularly used in the Stormwater Capital Program for project selection and cost-effectiveness assessments.

Headwater wetland restoration projects

Headwater wetland restoration projects are now considered to be priority projects for the Stormwater Capital Program. Stormwater and water quality grants have been secured, however larger streamflow supplementation grants, which would allow bigger, more effective projects to be built, have not, as of this date.

“One Water” systems

Clark County is initiating discussions with county school districts on constructing stormwater capture and reuse projects for the irrigation of school ball fields.

Trench dams in pipe trenches

The use of trench dams on storm and sanitary sewer systems in shallow groundwater areas is now standard practice on county road projects. Trench dams are considered to be potentially very effective in reducing groundwater discharges and maintaining high groundwater elevations.

Fairly extensive pipe inflows due to increased groundwater pressures occurred on one early project. That experience led to the need for, and subsequent development of, improved pipe joints.

These inexpensive trench dams complement and improve the performance of Low Impact Development techniques, which are themselves becoming established practice.

7.3 National and International examples

Although not developed using the organizing principle, these national and international initiatives are considered to be representative of the types of outcomes that may be expected when an entropy-based resource management approach is used to develop sustainability strategies.

Portland, Oregon: Turbines in gravity water lines

The City of Portland generates electricity through the use of turbines installed in their gravity-fed water pipes. Converting the kinetic energy in the streamflow into useful electrical energy constitutes logical and orderly optimization of available energy resources. This holistic practice can also be viewed as a good example of the frugal use and effective storage of resources.

Mozambique: The PlayPump

Here, a merry-go-round uses the power of children at play to pump groundwater to an above ground storage tank, so providing a valuable water supply to African villages. As for walking and cycling, readily available “people power” is used where other energy sources may be unavailable, inadequate, harmful or overly expensive.

Though being an excellent energy/water supply match-up, with additional recreational and health benefits, implementation has proven difficult due to poor quality of groundwater, inadequacy of supply and other logistical problems.

Interestingly, from the point of view of entropy-based resource management, their use has been criticized as to whether children playing is an appropriate source of energy for water supply and other infrastructure purposes; once set up, a lot of “play” might be needed to maintain the expected supply.

Costa Rica: Sustainable mobility

A “first people, then vehicles” sustainable mobility transportation strategy is being used to reduce energy use and pollution. The strategy has made an important contribution to decarbonizing Costa Rica’s economy and helping them meet their Paris Climate Agreement and UN Sustainable Development Goals.

Denmark: Kalundborg Industrial Symbiosis

The Kalundborg Industrial Symbiosis is a public-private consortium where multiple industrial companies collaborate in taking a “circular approach” to production and waste management. With symbiosis, the “residue” from one industrial company (previously “waste” and coming with pollution issues) becomes the “resource” for another company.

The Kalundborg Symbiosis may be viewed as “a holistic process that mimics natural systems”. Alternatively, the prior waste of useful residual materials (and subsequent pollution) may be viewed as an illogical or disorderly component of that industrial process; finding a recipient who can make useful, profitable use of that residue can be thought of as bringing order into the manufacturing process.

Singapore: Tengah Eco Town

Singapore’s latest new settlement is envisioned as a smart, sustainable new town, and is considered to represent the future of sustainable urban design in Singapore.

The town plan includes centralized cooling (important in hot, humid Singapore, and becoming more critical with the changing climate), automated trash collection and a car-free town centre, all serviced by smart infrastructure. The advent of electric driverless cars and autonomous vehicles (separated motorized vehicle routes are generally underground) was anticipated and provided for at the very start of the planning process.

Tengah represents a good example of holistic, smart, sustainable and resilient town planning, the embodiment of the entropy-based planning approach advocated in this series of technical papers.

8 "The sustainable city"; development of a sustainable land use plan

This paper and body of research has introduced use of the entropy-based resource management organizing principle as a means of developing sustainability strategies in the areas of water resources, transportation and land use planning.

The paper also showed that a well-thought out entropy-based sustainability approach can help address challenges arising from climate change. Entropy-based strategies and their supporting mathematical techniques can also help provide the algorithms needed for AI-enhanced infrastructure to further improve efficiencies within the transportation system, including the successful integration of autonomous vehicles and driverless cars.

All can be accomplished in a holistic manner, with each individual strategy supporting all others in a "virtuous cycle" or "positive feedback loop".

By way of illustration, an Entropy-based Resource Management Plan for a "Sustainable City" focused on the energy, water and air resources needed for life in that city is outlined below.

8.1 Energy

An entropy-based resource management plan for our energy resources would:

- Eliminate unnecessary work;
- Employ entropy-based transportation strategies to minimize the work needed for home-to-workplace travel and all other trips; and,
- Develop energy-efficient, non-polluting vehicles to perform that work as efficiently as possible.

Supporting strategies would include:

- Maximize telecommuting;
- Minimize home-to-workplace travel distance and time; and,
- Multi-modal transportation systems.

Implementation measures may include a sustainable land use plan that merges econometric analyses with entropy-based transportation systems. On-going operations would rely heavily on the use of AI and "Smart City" technology.

Other compatible measures include "Complete Streets", "20-Minute Neighbourhoods", "First Mile" transportation options, roundabouts, entropy-based traffic signal optimization, vehicle-activated traffic signals and entropy-based limits on urban sprawl.

Supporting private initiatives include the increased use of solar energy, wind energy linked to pumped storage or underground injection of compressed air, turbines inside gravity water supply lines, electric vehicles, autonomous vehicles and driverless cars, improved batteries, artificial photosynthesis for fuel.

8.2 Water

An entropy-based resource management plan for our water resources would:

- Establish and maintain high groundwater elevations in all places at all times.

This will maximize retention of the annual rainfall supply within the watershed, which in turn will maximize the residence time and general availability of water throughout the watershed.

Supporting strategies are:

- Infiltration-retention-detention hierarchy for disposal of stormwater runoff;
- Flood flow capture and aquifer replenishment;
- Headwater wetland restoration projects; and,
- Trench dams in pipeline and utility trenches.

Implementation can be achieved by incorporating a water resources-based envirometric overlay within the sustainable land use planning process. In the absence of a detailed land use plan, “pump up the groundwater then plant everywhere” can serve as a reasonable envirometric *game plan* for a community faced with sustainability and resiliency challenges.

Other compatible measures include Low Impact Development BMPs, Green Streets, “One Water” strategies, Smart Infrastructure.

8.3 Air

An entropy-based resource management plan for our air resources would:

- Increase photosynthesis; and,
- Reduce greenhouse gas emissions.

Supporting strategies are:

- Entropy-based water resource management strategies will increase the availability of water to encourage photosynthesis and vegetation growth, energy production and removal of carbon dioxide from the atmosphere; and,
- Entropy-based transportation strategies will reduce greenhouse gases and improve air quality.

Implementation can be achieved though use of a sustainable land use plan developed using econometric analyses integrated with entropy-based transportation and water resource management strategies.

Other compatible measures include reforestation, electric vehicles.

Summarizing, this series of technical papers suggests that the entropy-based resource management organizing principle may be used to develop a Sustainable Land Use Plan, serviced by a sustainable transportation system, supported by smart, sustainable, resilient infrastructure systems, whose operation is further enhanced by the use of AI technology. Following up on that suggestion will be the principal objective of this research from this point forward.

9 Discussion

The great progress that has been made since the Industrial Revolution has been in pursuit of improving the liveability and quality of life of our communities. While much has been achieved, there have also been negative impacts from our industrial processes and general resource management practices that detract from that progress. Burning fossil fuels and deforestation both increase the amount of carbon dioxide in the atmosphere, contributing to global warming and changing our climate. Industrial waste product discharges pollute our rivers, groundwater and drinking water supplies.

These effects, once assumed to be sufficiently dispersed and diluted in nature to produce negligible impacts, are now known to have very significant impacts on the environment we live in, threatening our liveability, even sustainability. Discounting system “externalities”, like greenhouse gas emissions, produces unintended consequences.

Those negative impacts continue, and worsen, in spite of all the measures we are currently taking to avoid or mitigate them. And so we need to change and improve what we’re doing in our resource management if we are to maintain liveability and achieve long-term sustainability. We now need to consider all our natural resources at all times, and we also need to improve the effectiveness of all our interdependent management processes and systems.

A way forward may be found in the philosophy of holism. Holistic resource management would fully account for all resources, while at the same time generating the additional management efficiencies (“the whole is more than the sum of its parts”) that will be needed to meet today’s challenges at affordable cost.

While a thoughtful and well-considered *qualitative* application of holistic resource management can produce excellent outcomes, expressing that philosophy in terms of fundamental physics can add scientific rigour and bring improved quantification to the process. “Entropy-based resource management” is offered here as that physical expression of holistic resource management.

In particular, this paper and line of research has promoted the use of entropy-based resource management in its most basic and wide-ranging form, i.e. as an “organizing principle” for developing sustainability strategies. As such, it can be considered a holistic, “back-to-basics” approach to sustainability, its purpose being to prompt the discovery of new practices and combinations of practices that have not yet been discovered or implemented, while at the same time improving the effectiveness of existing best management practices.

While simple, qualitative and semi-quantitative analyses are emphasized, the paper also notes that there are many more refined examples of entropy-based analyses, particularly in the transportation and land use planning fields, that can help bring greater quantification and precision to individual strategies coming under the broad envelope of entropy-based resource management. Powerful entropy-based mathematical techniques in Systems Analysis and Information Theory can help develop solutions for the most complex problems, while still remaining entirely consistent with the organizing principle.

The focus on physics and entropy ensures that the widest range of potential solutions is available for any problem, at any time, in any location having any particular physical characteristics. A particular challenge at this time is the need to find effective energy storage for intermittently operating wind and solar power-generating facilities. With an entropy-based approach, the full range of physical, chemical and biological solutions is available at all times to fit any particular situation's renewable energy storage needs. For example, pumped storage, improved batteries and artificial photosynthesis, or any combination of them, may be selected based on a particular location's specific attributes and characteristics.

On the management and administration side, the organizing principle aims at ensuring that there are no logical inconsistencies or gaps between how physical processes actually function and how all our resources are managed and administered. As dwindling resources become ever more scarce, a management focus on achieving this basic goal becomes ever more needed and urgent.

Recasting sustainability in this way, that is as an applied physics/engineering problem, may be particularly timely, since the introduction of driverless cars, smart technology and Artificial Intelligence technology into our cities and infrastructure also needs to be facilitated by our sustainability planning. Engineers will be designing, building and operating all the above and, again, we should do so holistically.

Engineers, and the Mechanics' Institutes who taught us, have always listened to our citizens and given them what they need to be healthy and happy. Next time your community is pleading with you for a sustainable economy and environment, consider using entropy-based resource management to give them just that.

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